# High-Lift Common Research Model: RANS, HRLES and WMLES perspectives for $C_{L\max}$ prediction using LAVA

Cetin C. Kiris, Aditya S. Ghate, Jared C. Duensing, Oliver M. F. Browne, Jeff A. Housman, Gerrit-Daniel Stich, Gaetan K. Kenway, Luis S. Fernandes, Leonardo G. Machado

**Computational Aerosciences Branch**

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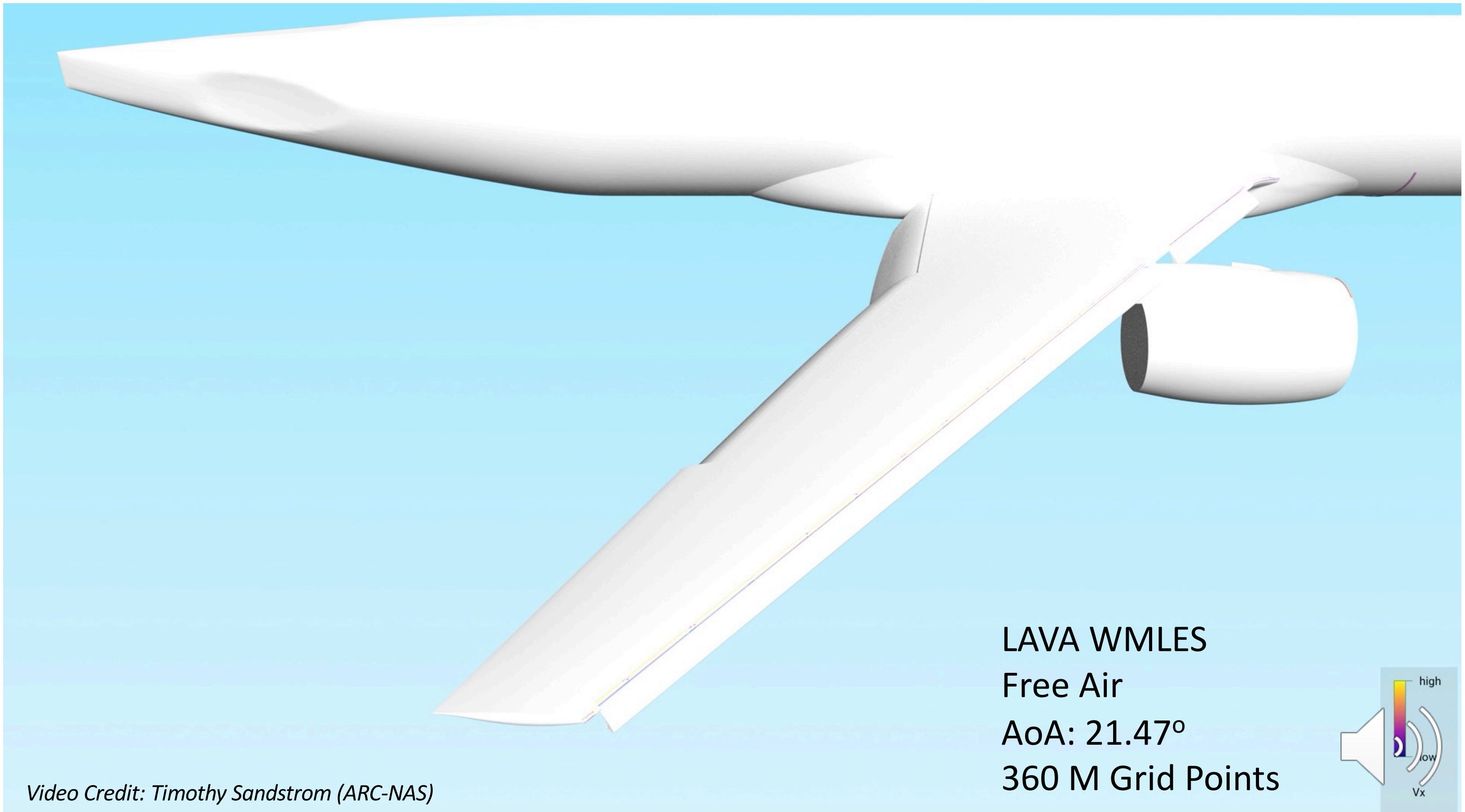
# Objective

Investigate best-practices for aerodynamic predictions of high-lift configurations through a full angle-of-attack sweep including $C_{Lmax}$ and stall

- On validity of RANS for $C_{Lmax}$
- Does HRLES improve RANS?
- Is WMLES a capable tool for $C_{Lmax}$ and stall?
- Comparison of free-air results between methods
- Wind Tunnel vs Free Air Simulations
- Cost comparisons



# Computational Approach

All methods use curvilinear overset structured grid, compressible NS formulation

**RANS**

- HLPW4 Committee curvilinear grids
- SA closure with corrections
- $3^{rd}$ order Roe + Koren limiter
- ILU(1) Preconditioned GMRES

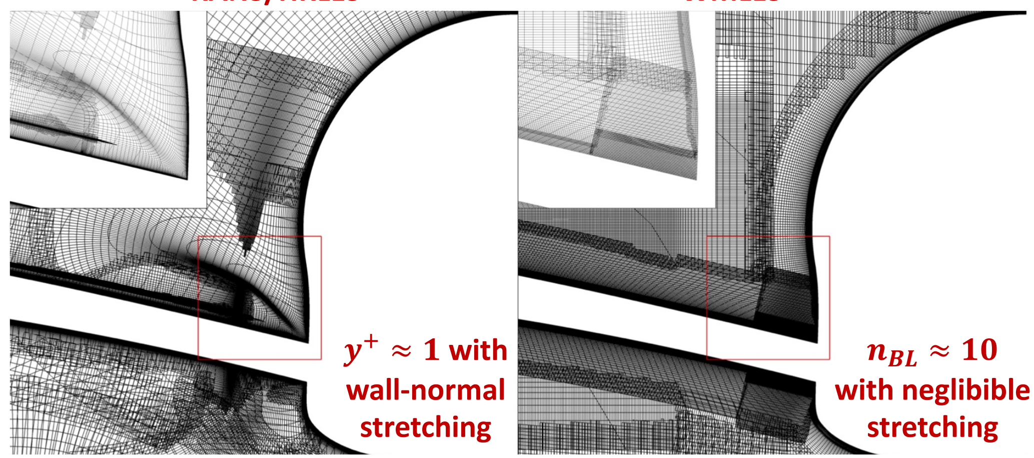
**HRLES**

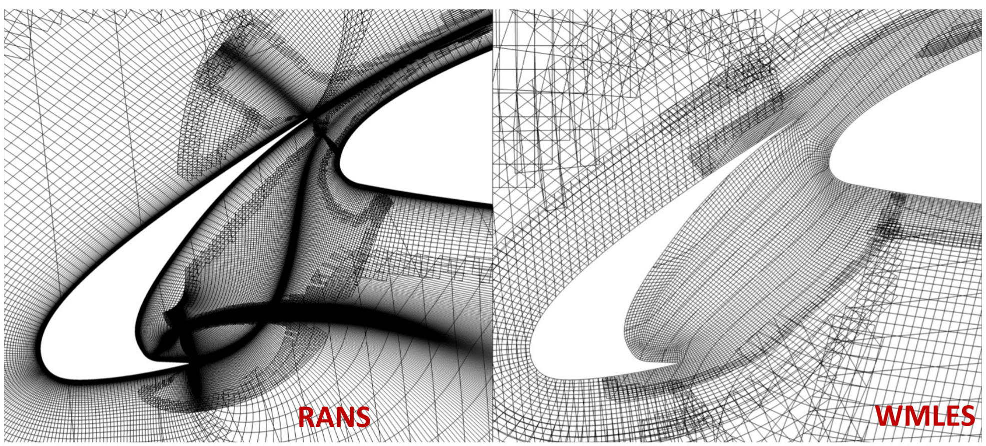
- Further refinement of RANS surface grids
- ZDES-Mode 3 Enhanced Protection (Deck & Renard, 2020)
- HWCNS – WENO3 and/or $4^{th}$ order central
- BDF2 Time stepping

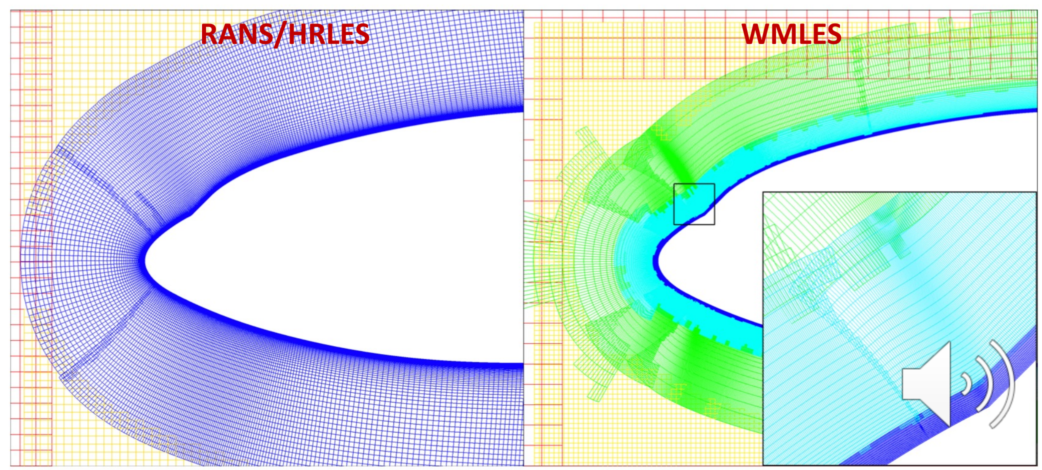
**WMLES**

- Distinct topologies from RANS
- Constant-coefficient Vreman model
- Algebraic wall-model
- Sensor based blending between $3^{rd}$ order and $4^{th}$ order spatial discretization
- RK3 Time stepping

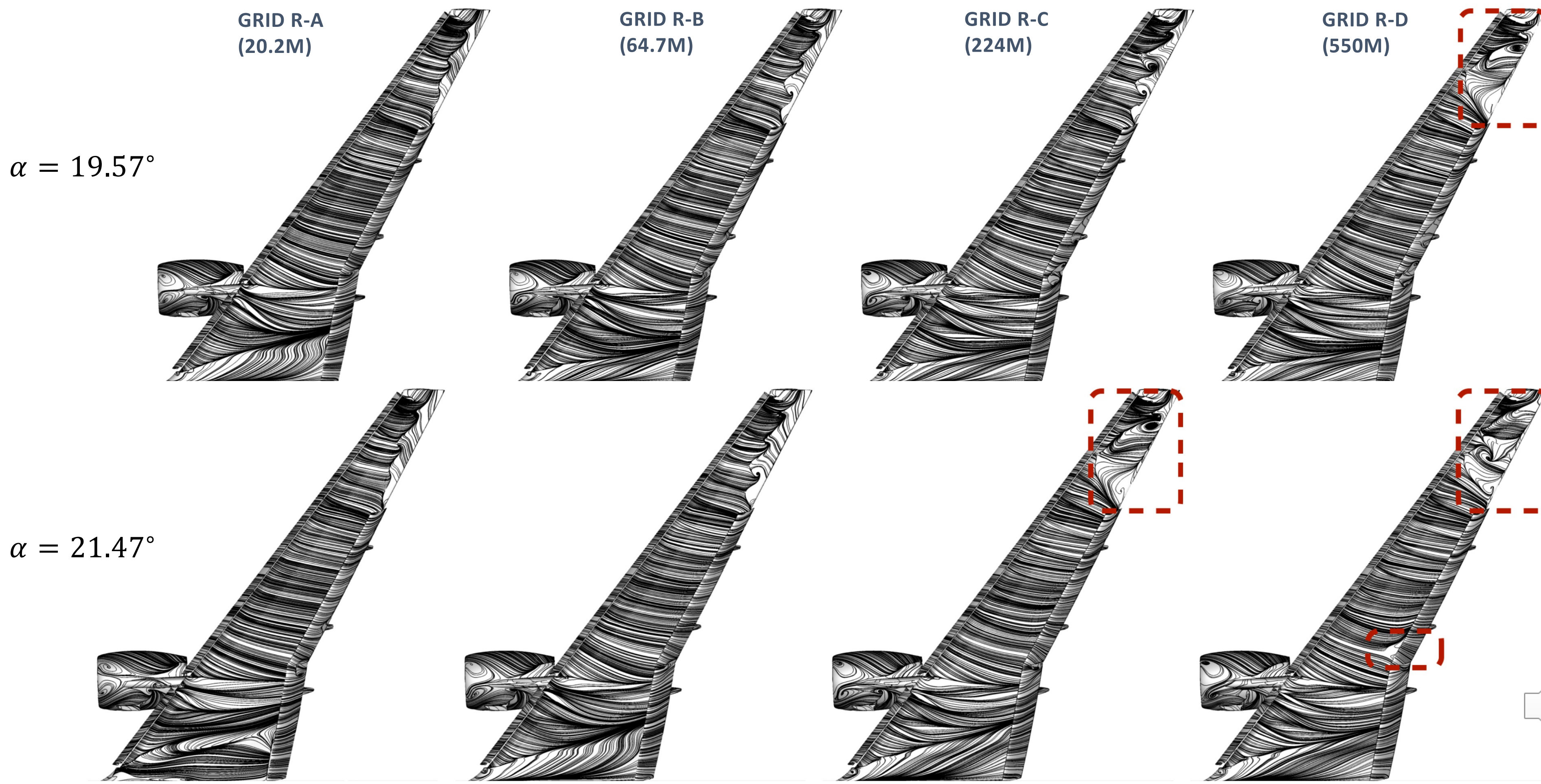
**RANS/HRLES** **WMLES**



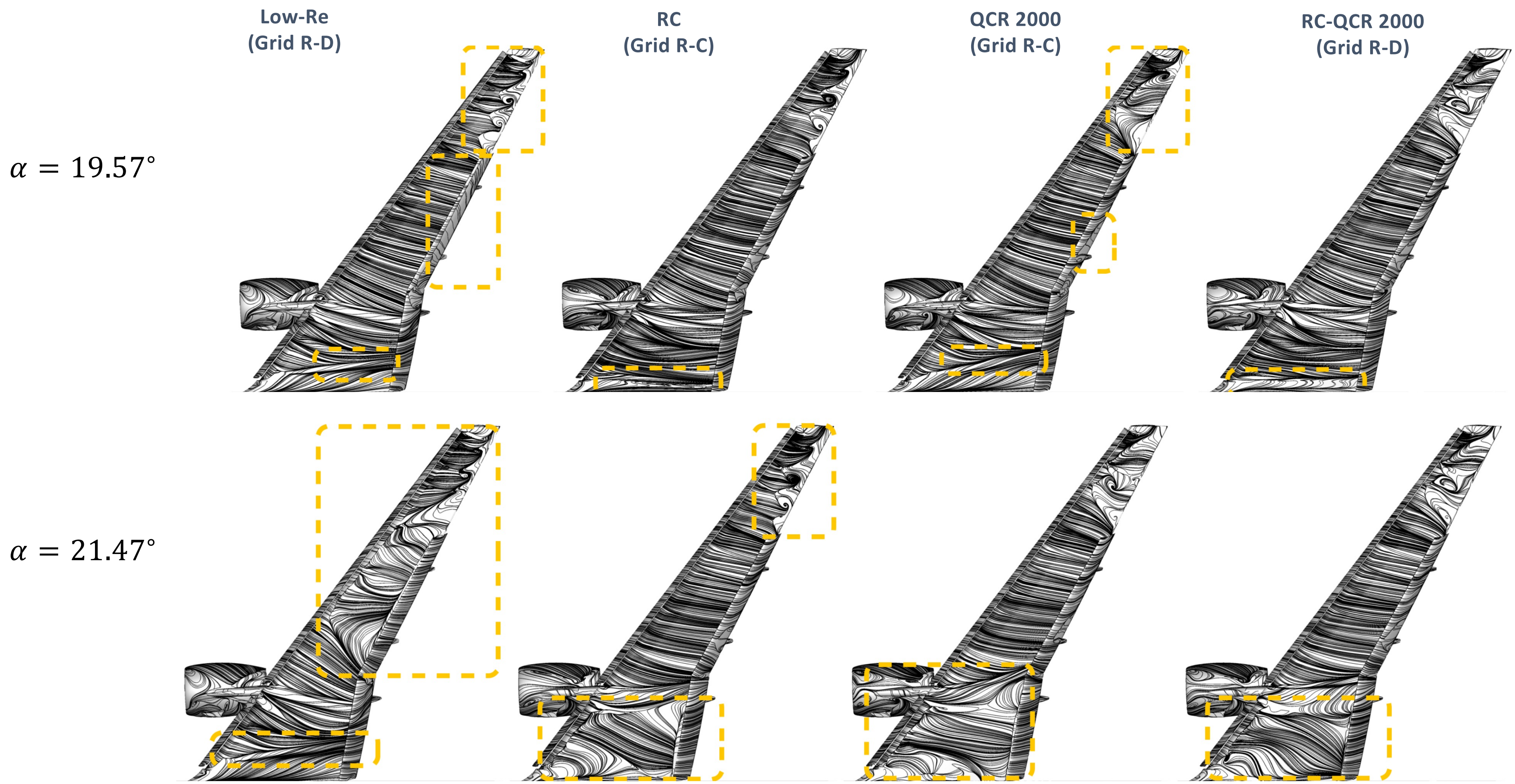



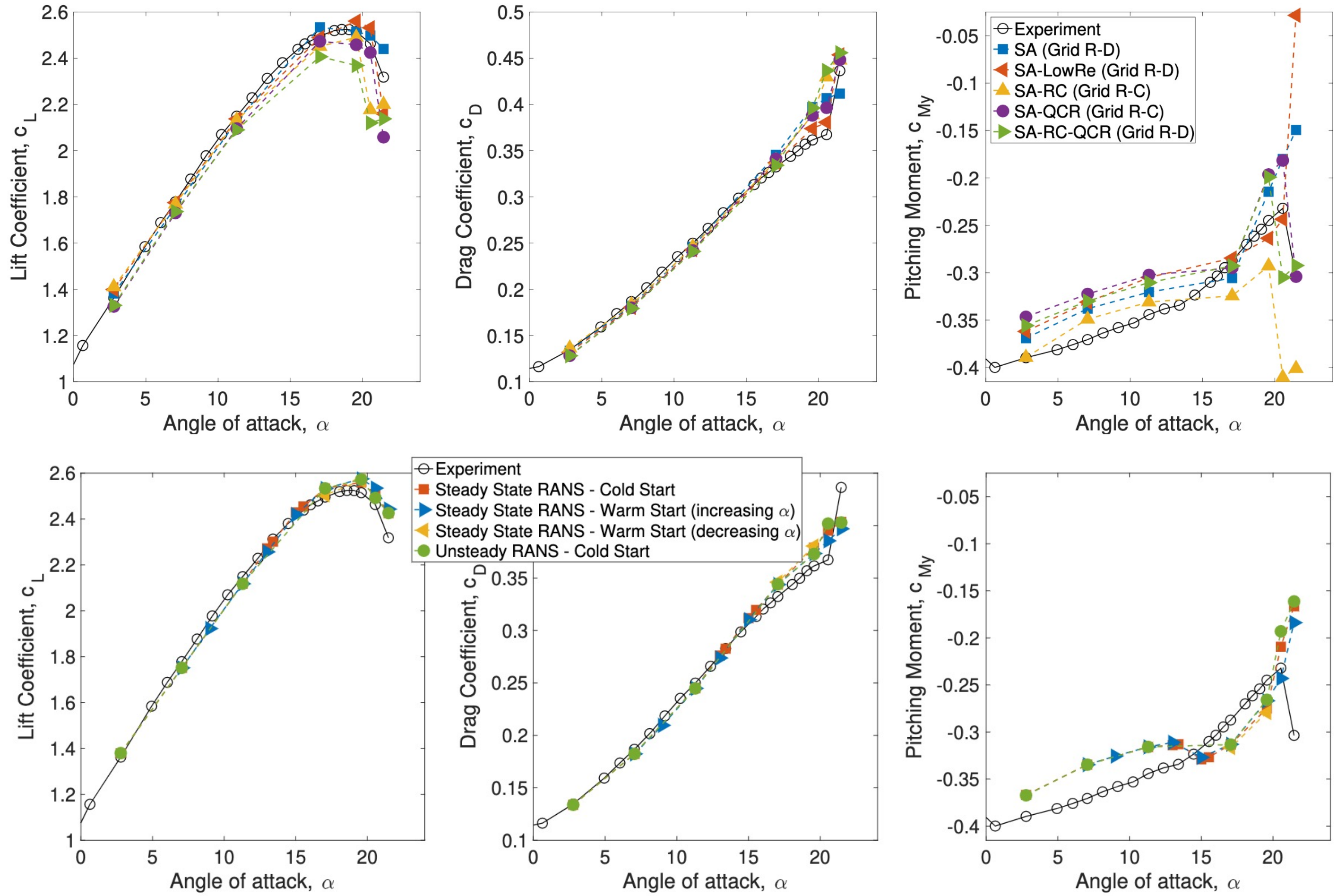
# RANS Simulations (Baseline SA) – Grid sensitivity



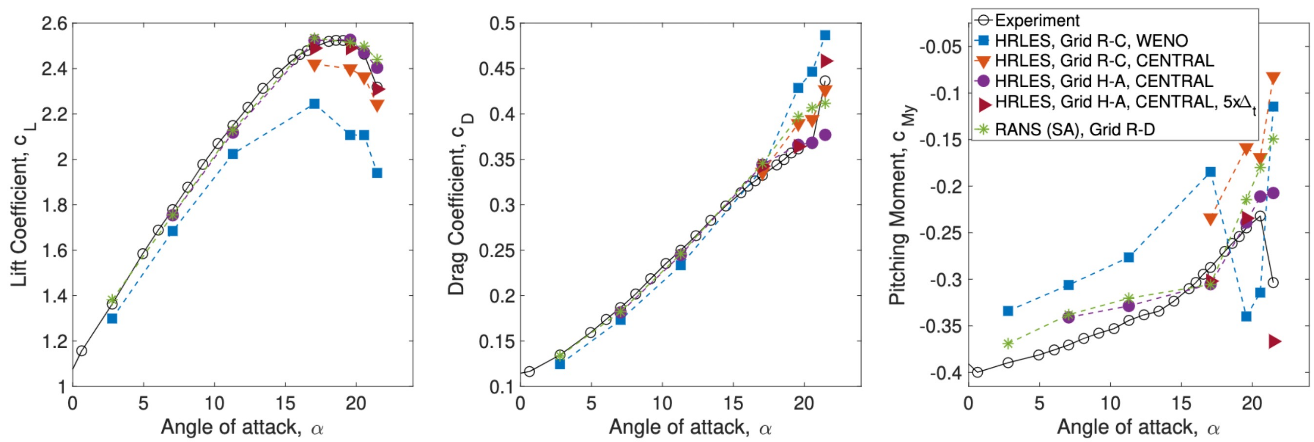
# RANS – SA Correction Terms

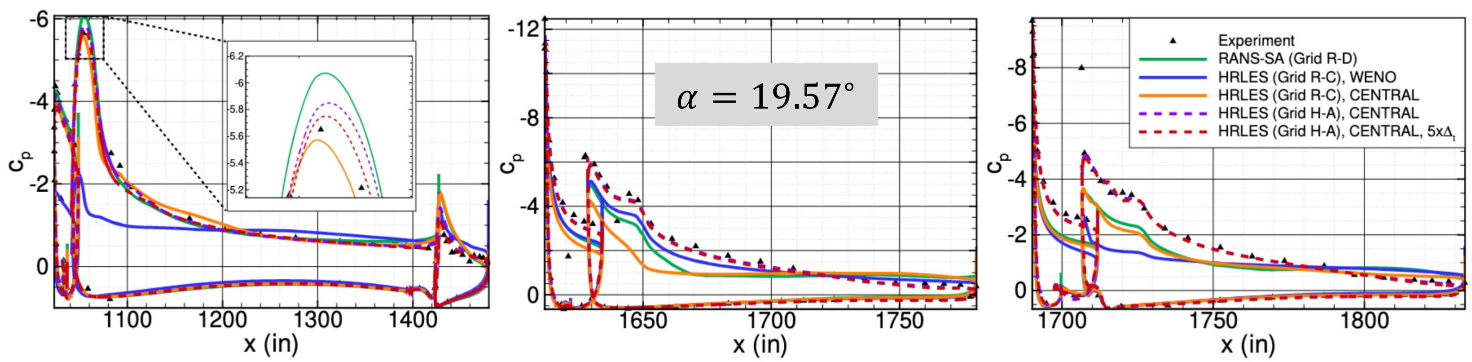


# RANS – SA Variations and Simulation Procedure



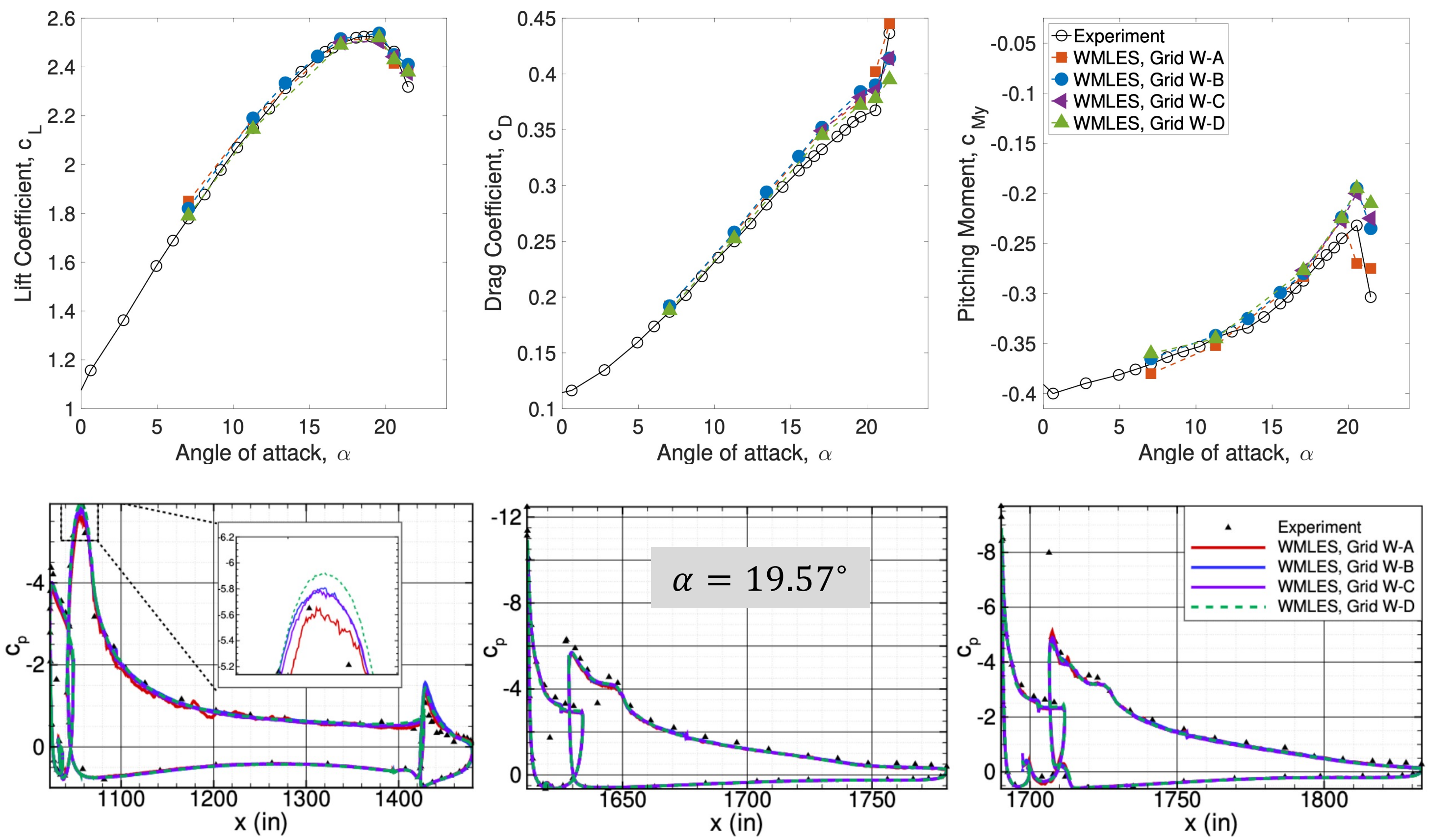
# HRLES – Improvements over RANS




(a) Slice A, $\eta = 0.15$ (b) Slice G, $\eta = 0.82$ (c) Slice H, $\eta = 0.91$

# WMLES – Grid Sensitivity and “Convergence”

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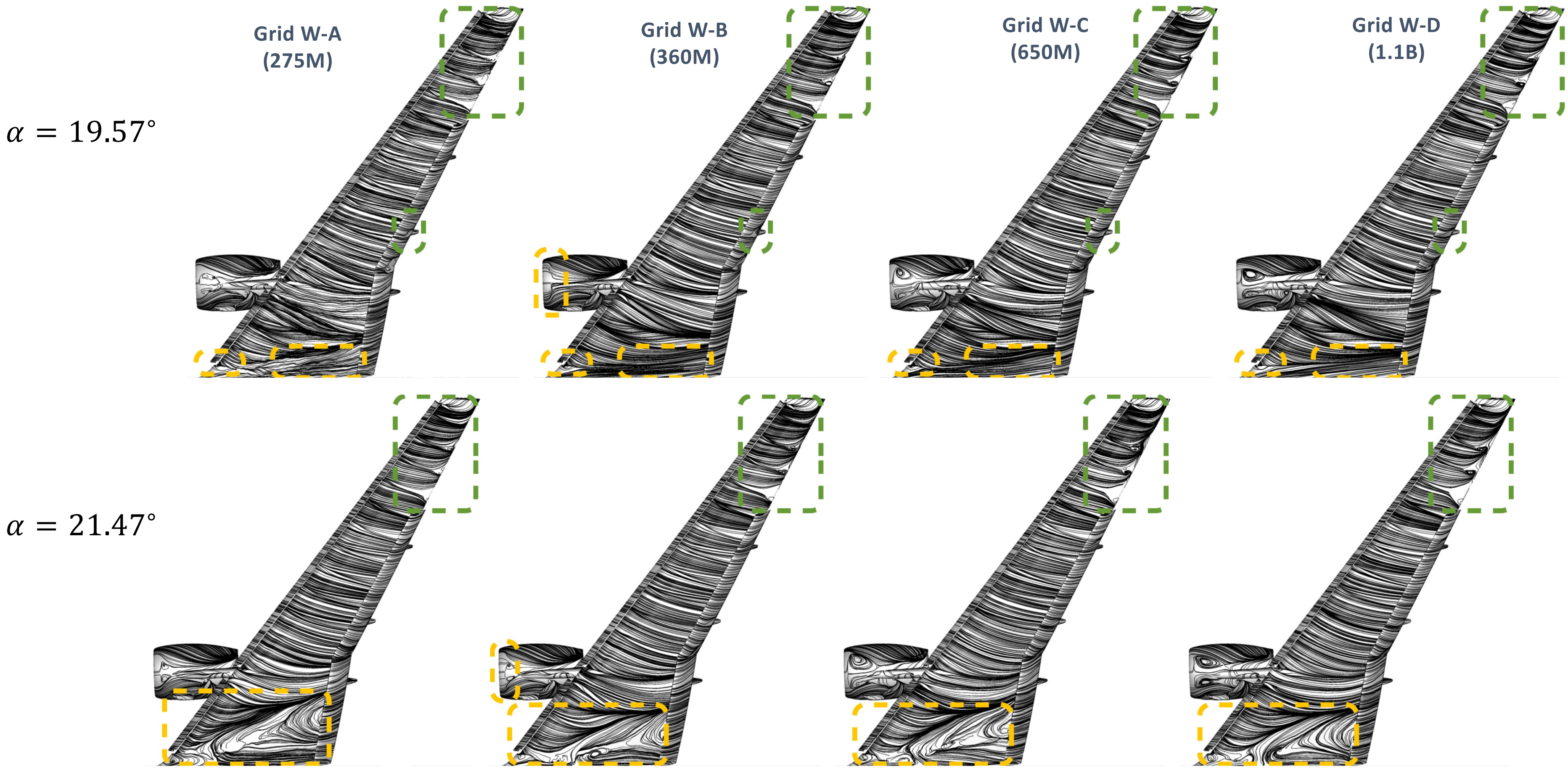
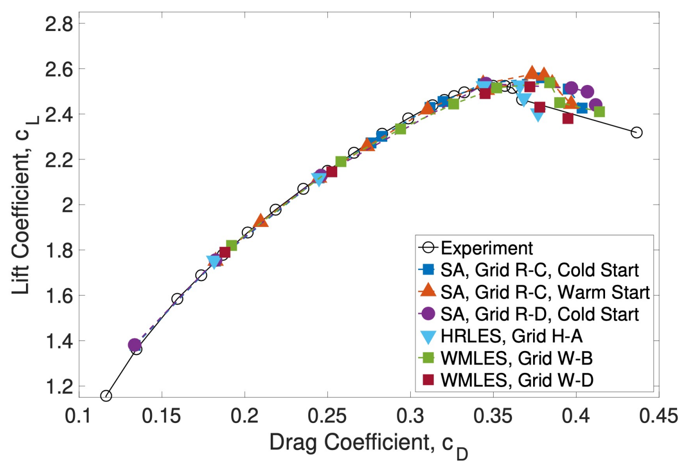
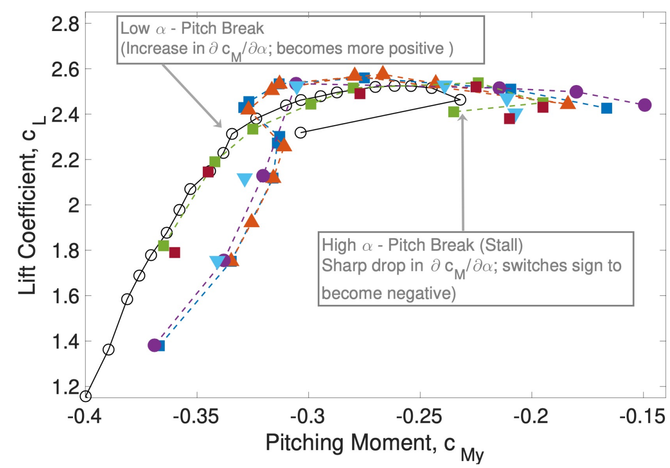
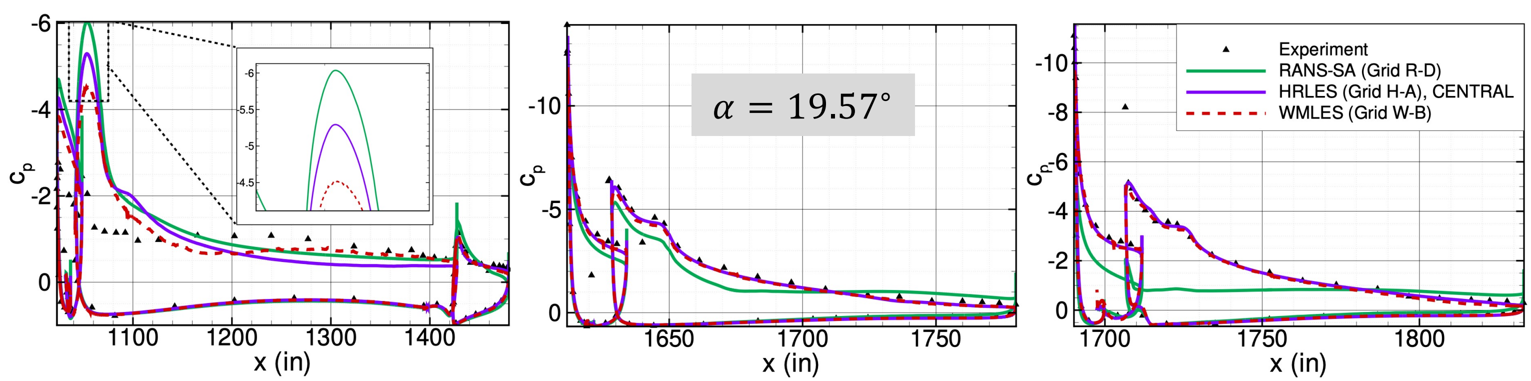


# Comparison Between Methods (Free-Air)

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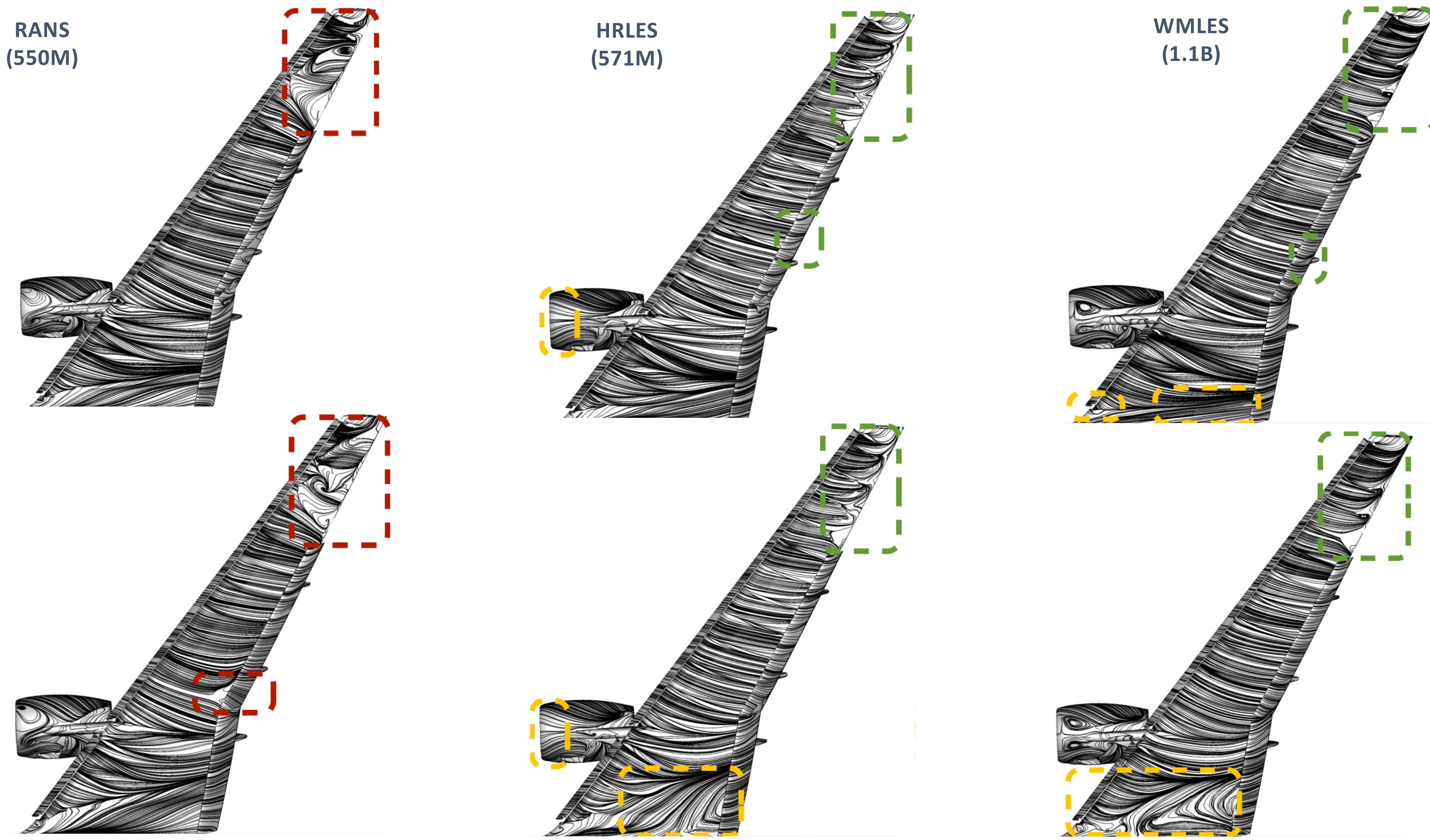
# Comparison Between Methods (Free-Air)

$\alpha = 19.57°$

$\alpha = 21.47°$



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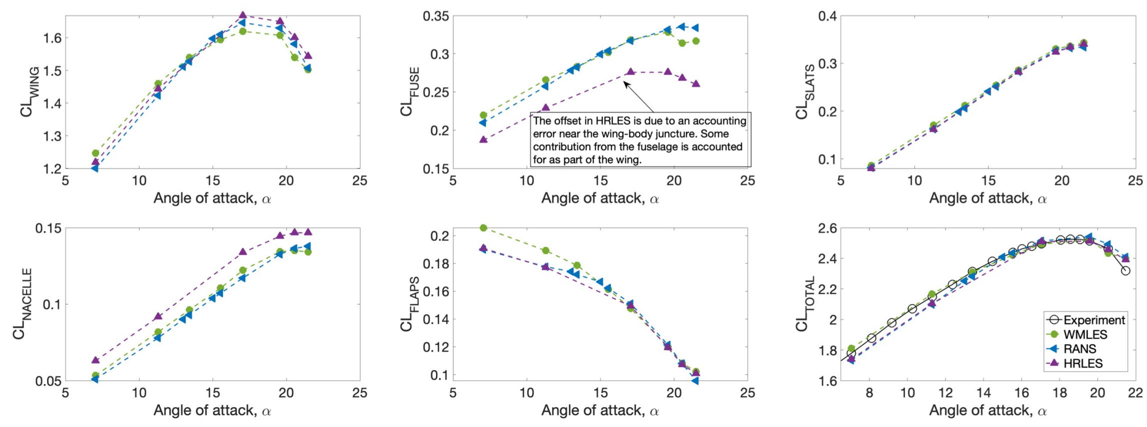
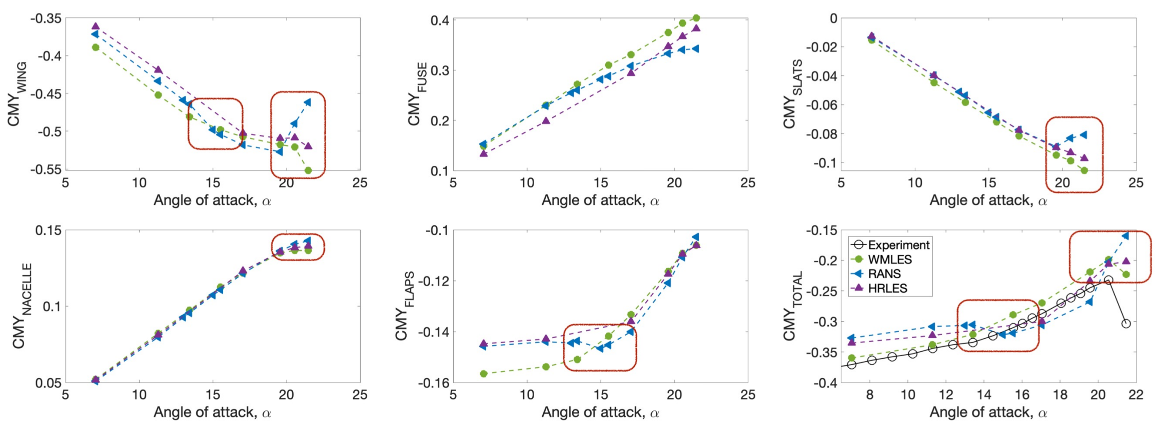


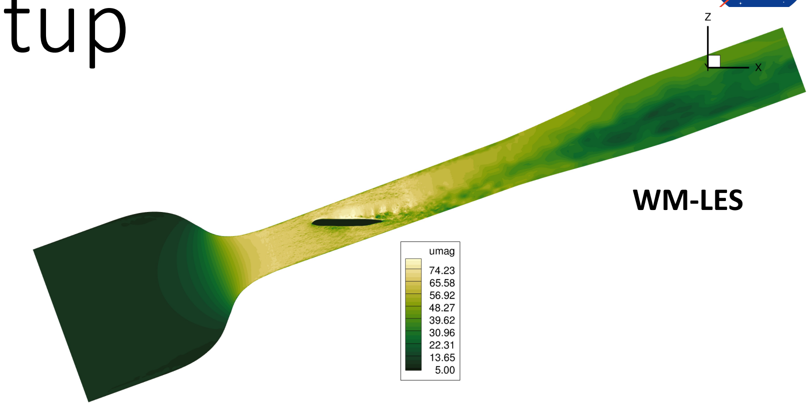

(a) Lift coefficient




(b) Pitching moment coefficient

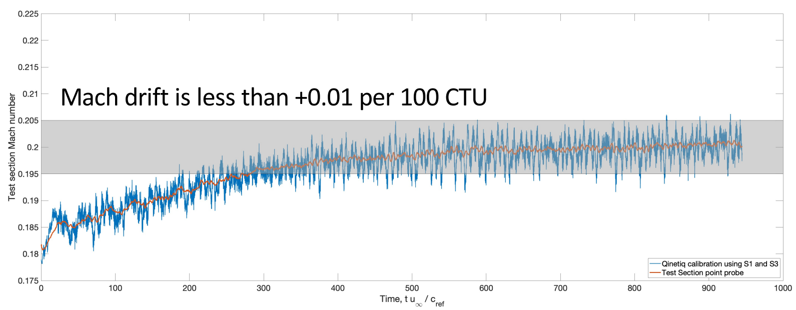
- Both WMLES and HRLES predict a high-alpha pitch break in the wing-integrated moments
- RANS predicts an opposite high-alpha break due to onset of large-scale spurious outboard separation
- The low-alpha pitch break seem to occur due to sudden loss-of-lift on the flaps; WMLES appears to predict the correct trend, but RANS shows abnormal behavior
- All methods clearly over-predict lift after CLmax is reached

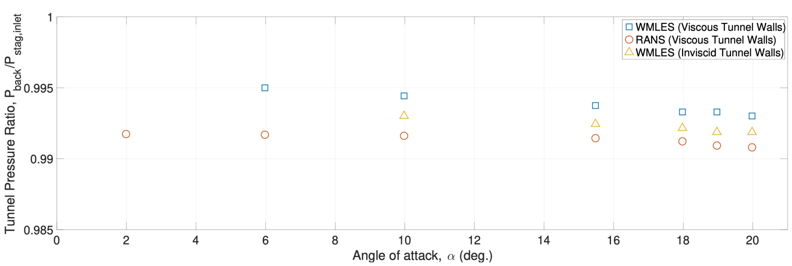
# Tunnel – initialization and setup

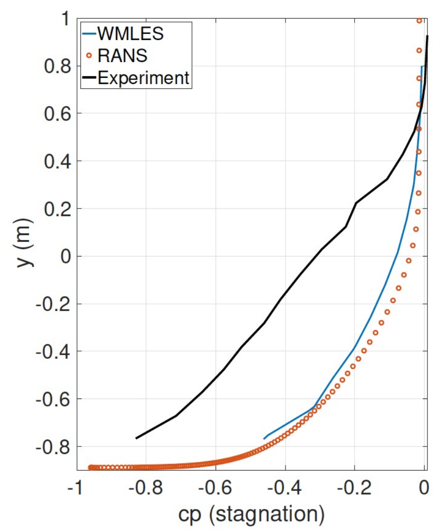


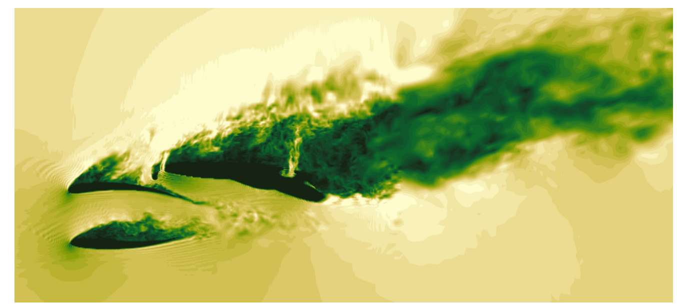

**Two precursor simulations: WM-RANS + WM-LES (coarse)**

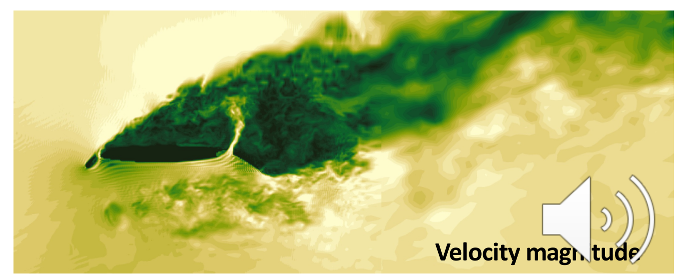
- "Coarse-representation" of model geometry to capture blocking effect
- Full grid is approximately 77M compute points; time step is 25x larger than GridB WMLES
- Roughness treatment used in upstream convergent section to "thicken" test section BL
- Fixed back-pressure (obtained from WM-RANS, with BL calibration)
- Precursor computational costs are approx. 10% that of a 50-CTU gridB simulation



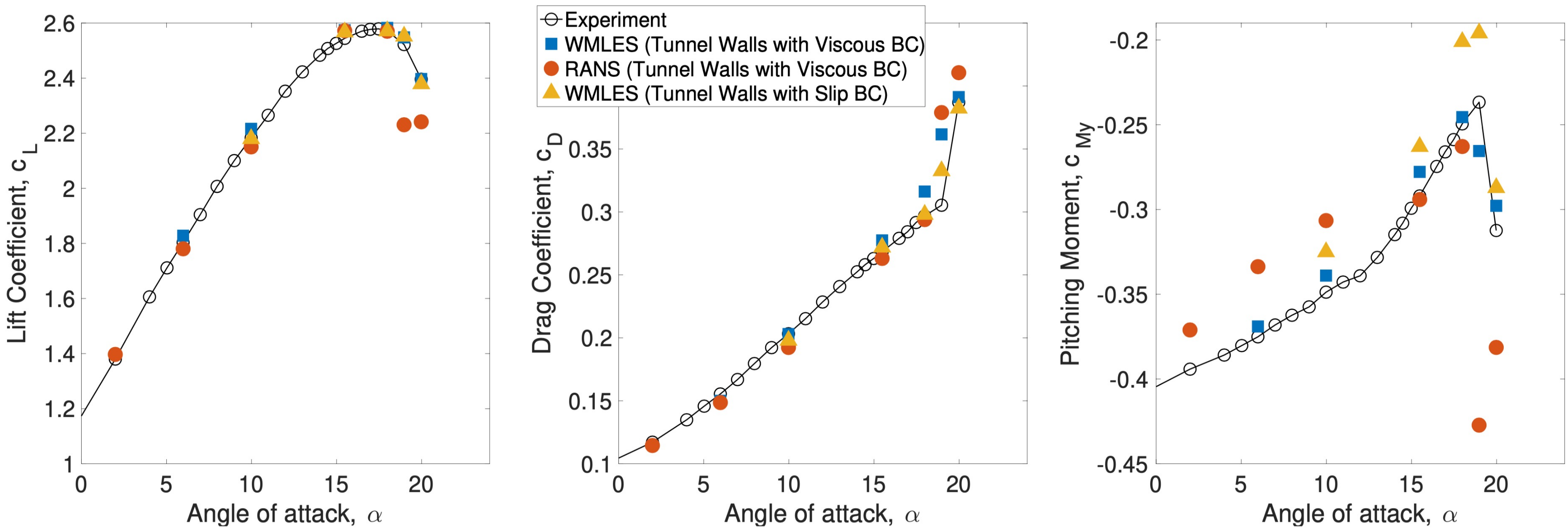



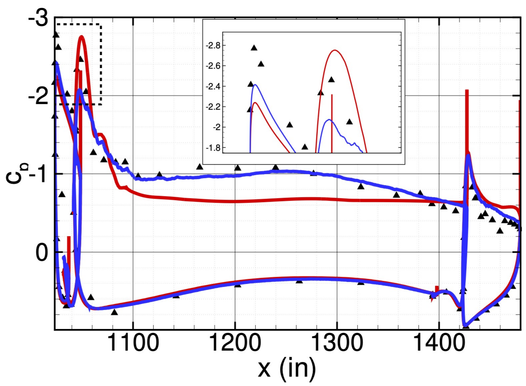





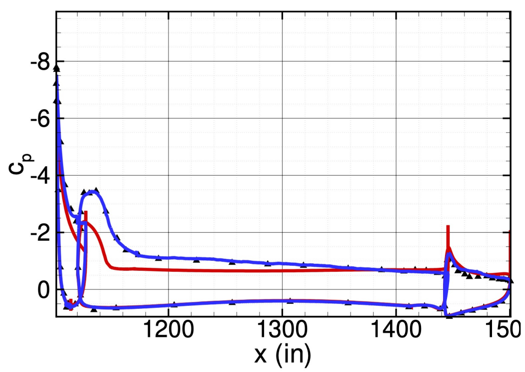
# Tunnel – Loads compared with experiment



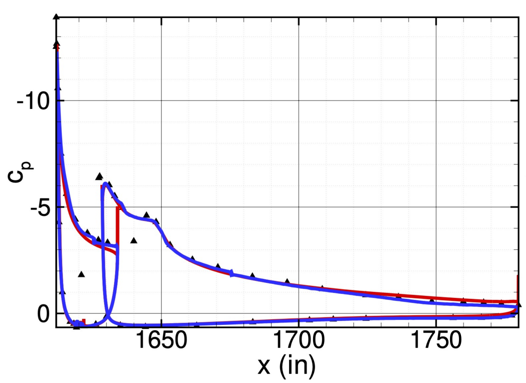
# Tunnel – RANS vs WMLES



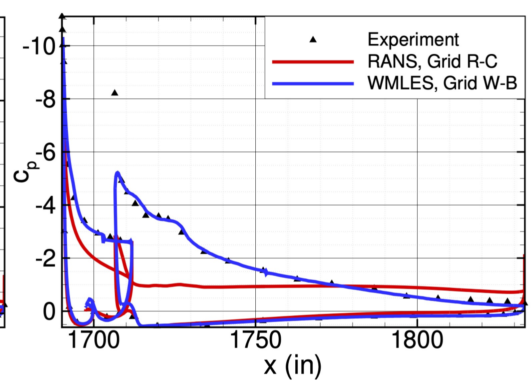

(a) Slice A, $\eta = 0.15$




(b) Slice B, $\eta = 0.24$



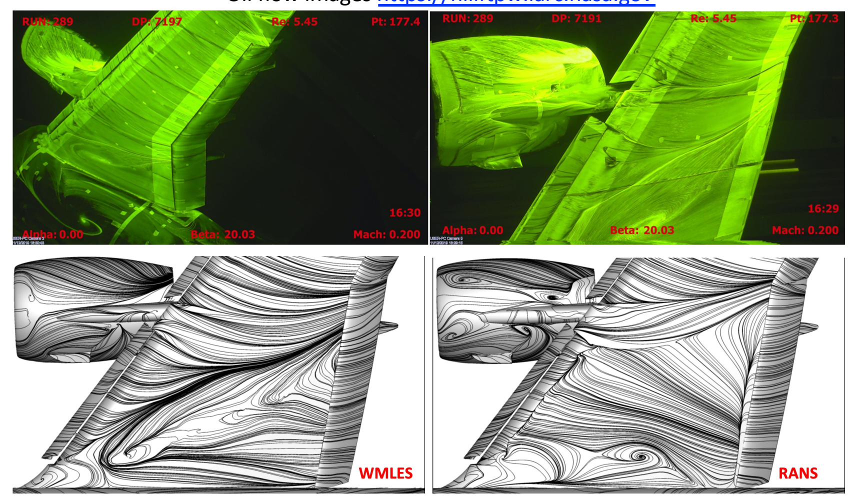

(c) Slice G, $\eta = 0.82$



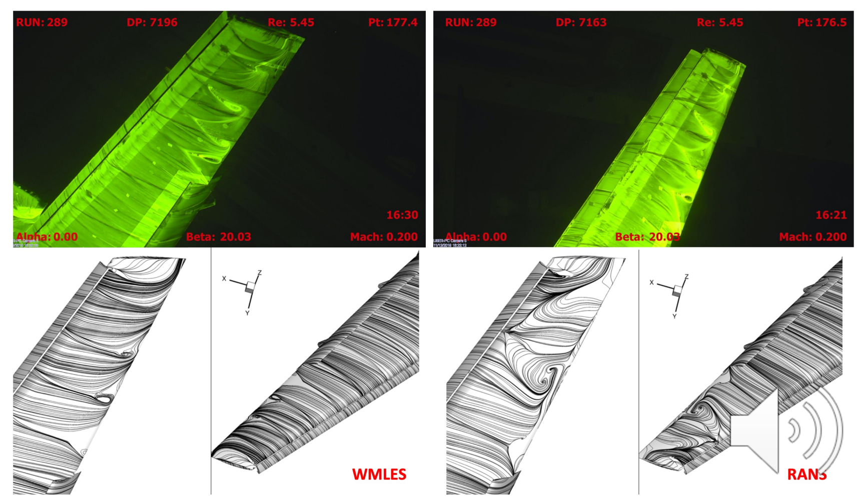

(d) Slice H, $\eta = 0.91$

$\alpha = 19.98°$

Oil flow images https://hiliftpw.larc.nasa.gov




(a) Inboard/Wing Root




(b) Outboard Wing

# Cost – Are scale resolving methods competitive?

| Attribute | Simulation Methodology | | | | |
|---|---|---|---|---|---|
| | RANS (Steady) Grid R-C | RANS (Steady) Grid R-D | RANS (Unsteady) Grid R-C | HRLES Grid H-A | WMLES Grid W-B |
| Solve Points | 223M | 550M | 223M | 571M | 360M |
| Timestep size | - | - | $2.57 \times 10^{-3} s$ | $2.0 \times 10^{-4} s$ | $3.5 \times 10^{-6} s$ |
| Nodes used for benchmark | 35 Skylakes (40 cores/node) | 100 Broadwells (28 cores/node) | 70 Broadwells (28 cores/node) | 200 Skylakes (40 cores/node) | 100 AMD Romes (128 cores/node) |
| Core-time per compute point per timestep | - | - | $354.36 \mu s$ | $139.5 \mu s$ | $2.03 \mu s$ |
| Timesteps per CTU | - | - | 40 | 514 | 29338 |
| Core-time per CTU | - | - | 901 hours | 11360 hours | 5970 hours |
| Simulation time needed for $\alpha = 19.57°$ | - | - | 150 CTU | 50 CTU | 50 CTU |
| Core-time needed for $\alpha = 19.57°$ | 21,000 hours | 44,800 hours | 135,150 hours | 560,000 hours | 298,500 hours |
| **NAS SBUs needed for** $\alpha = 19.57°$ | **835** | **1,600** | **3,560** | **22,120** | **9,470** |
| **Relative Cost over typical RANS** | **1.0** | **1.9** | **4.25** | **26.4** | **11.3** |

# Summary

- **Shortcomings of RANS for CLmax**
  - Drag polar is accurate at low-angles of attack, but abnormal trends observed in pitching moments – possible incorrect flow topologies on flaps?
  - At $C_{Lmax}$ – strong sensitivity to both grid (on the outboard wing) and SA model corrections (inboard wing) seen
  - In-tunnel simulations show excess inboard and outboard separation inconsistent with oil-flow and CP data from experiments
- **Does HRLES mitigate challenges of RANS?**
  - HRLES does show measurable improvements over RANS near $C_{Lmax}$ in terms of improved outboard flow-topologies and pitching moment predictions
  - Improvements over RANS only achieved when an LES-appropriate grid and an LES-appropriate discretization is utilized
  - Sensitivity is also reported for time-step size post $C_{Lmax}$ with excessively large time steps resulting in unphysical wing-root separation in the free-air
- **Is WMLES suitable for $C_{Lmax}$ problems?**
  - WMLES offers substantial benefits over RANS in terms of a) Robustness (low sensitivity to parameters), b) Cost (competitive turn-around time) and c) Accuracy (both flow physics and engineering metrics)
  - Acceptable grid convergence is in CP and aerodynamic loading is observed at most angles, although: CMY shows sensitivity at both the highest and the lowest angles
- **Can free-air simulations reproduce the stall physics observed in the tunnel experiments?**
  - Both HRLES and WMLES show corner-flow separation in free-air but both predict a much weaker pitch break going from $C_{Lmax}$ to the stall state.
  - WMLES in-tunnel simulations show quite accurate predictions of pitch break with both wing root and outboard flow topologies showing promising agreement with experiment.
  - WMLES with slip-wall treatment for the tunnel side-walls highlight potential sensitivity of the post $C_{Lmax}$ stall onset phenomenon to the tunnel side-wall boundary layers
- **Future directions (will be addressed at Aviation 2022):**
  - Issues associated with thin leading edge boundary layers are the likely culprits with the WMLES problems. Further investigations will be performed.
  - Installations effects involving a) tunnel blockage, b) standoff/mount and c) side-wall boundary layers need to be investigated further using WMLES.
  - Further grid refinement studies in HRLES will be performed
  - Scalability in grid generation needs to be addressed: Use of octree-immersed boundary treatments for WMLES

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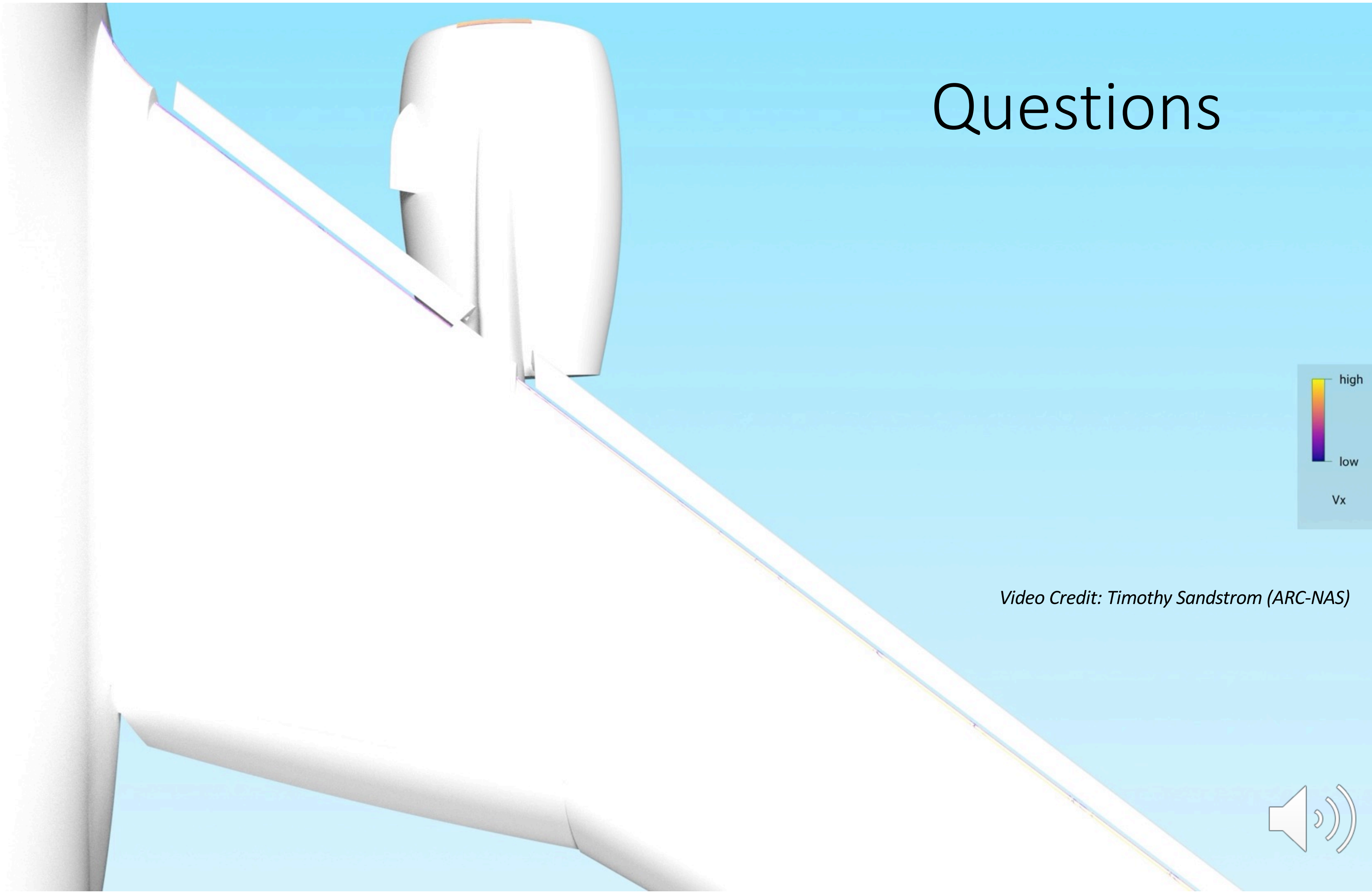
- Computer time has been provided by the NASA Advanced Supercomputing (NAS) facility at NASA Ames Research Center. A small subset of the simulations presented in the paper utilized NAS allocation on Amazon Web Services (AWS).

- Special thanks to
  - Chris Rumsey at NASA LaRC for his support during HLPW4 activities.
  - Elisha Makarevich for his help with overset grid generation during his stay at NASA Ames Research Center.
  - Michael Olsen, William Chan, Jacob Wagner, Mike Barad and the HLPW4 participants for valuable discussions.
  - Steve Heistand and Henry Jin for their support on AWS

# Questions




*Video Credit: Timothy Sandstrom (ARC-NAS)*